

Life cycle assessment of bio-based products: a disposable diaper case study

Nadia Mirabella · Valentina Castellani · Serenella Sala

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Abstract

Purpose In this study, a life cycle assessment of a bioplastic based diaper was performed. The product has several innovative elements, due to the implementation of eco-design principles, such as: (1) introduction of biopolymers (namely polylactic acid (PLA) and Mater-bi®), (2) relevant reduction of petrochemical plastics, and (3) minimization of energy consumptions and use of renewable energy in manufacturing. The aim of the study is to evaluate the environmental benefits gained through eco-innovation, while identifying further areas of improvement.

Methods The bio-based diaper has been evaluated using a “cradle-to-gate” analysis. The functional unit is one diaper, assuming an average size among the different commercial options. A case study of an enterprise in Italy (WIP S.p.A) was carried out to collect as much reliable primary data as possible. In order to highlight potential areas of improvement and to compare the environmental performance of the product, a sensitivity analysis based on three different impact assessment methods (adopting ReCiPe 2008, IMPACT

2002+ and Cumulative Energy Demand (CED)) and a comparison with a standard commercial diaper were performed. Finally, three possible end-of-life scenarios including composting of WIP diaper were hypothesized and tested.

Results and discussion Contribution analysis suggested that sourcing and production of raw materials used in WIP diaper manufacturing contributed most significantly to the potential environmental impacts. Adopting ReCiPe method, pulp, and sodium polyacrylate present the highest environmental burdens in WIP diaper system. Applying IMPACT2002+ method, PLA relative contribution to the toxicity increases, due to the generation of the electricity used in corn production and in PLA production phases. For both methods, impacts related to energy consumption of the WIP diapers’ production process look to be negligible. WIP diaper performance has room for improvement, since critical points were detected in the life cycle stages of raw materials used. However, the results of the normalization step, according to ReCiPe method, state that WIP diapers can bring environmental benefits, compared to standard ones. Moreover, if composting end-of-life scenario is included in the assessment, there is a significant improvement in WIP diaper environmental performance compared to a standard diaper.

Conclusions Integrating eco-innovation and eco-design principles in the production of the bio-based diaper leads to a better environmental profile, compared to the standard one. Nevertheless, there are several areas of concerns to be considered in order to further improve its environmental performance. So far, the possible improvements identified from the case study are: (1) the selection of biopolymers suppliers with better production systems from an environmental point of view, (2) the reduction of distances along the supply chain, and (3) the implementation of composting procedures for the end of life. In conclusion, the introduction of biopolymers in diaper composition could lead them to be preferable compared to standard diapers, but criticisms arise, which need to be solved, to avoid the risk of burdens shifting.

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N. Mirabella (✉) · V. Castellani · S. Sala
Department of Earth and Environmental Science,
University of Milan – Bicocca, Piazza della Scienza 1,
20126 Milan, Italy
e-mail: nadia.mirabella@unimib.it

N. Mirabella
e-mail: nadia.mirabella@gmail.com

V. Castellani
e-mail: valentina.castellani1@unimib.it

S. Sala
e-mail: serenella.sala@unimib.it

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1 Introduction

In sustainable production and consumption strategies, bio-based products are increasingly developed, produced, and used as a result of eco-innovation approaches aimed at reducing the use of non-renewable raw materials. Nevertheless, to comprehensively evaluate the environmental profile of bio-based products, it is paramount to carry out life-cycle based study, as being bio-based is not sufficient to be considered environmentally friendly. The word “bio-based” refers to products which are made from biotic raw materials such as plants and trees, which are renewable raw materials; hence, bio-based products could substitute fossil-based ones (European Bioplastics 2011a). This definition includes many possible applications within several market segments, characterized by high growth and strong diversification (European Bioplastics 2011a) such as biofuels and bioplastics. Depending on the application, different types of bioplastics are processed in these products, as biodegradable polymers such as starch-based plastics (i.e., polylactic acid (PLA) and Mater-bi®) and bio-based or partly bio-based commodity plastics such as bio-based polyethylene and polyethylene terephthalate. In recent years, both biofuels and bioplastics have experienced a great market expansion due to the need to find substitutes to fossil fuels and petrochemical compounds. The market is growing by roughly 20 % per year, and increase of more than 1.7 million tons by the year 2015 is projected. By 2013, the worldwide capacity of bio-based plastics could increase to 2.3 Mt and by 2020 to 3.5 Mt (Shen et al. 2009). Other projections confirm that bio-based items production will increase in the near future; hence, it is important to understand the opportunities and threats to these resources (Kemp-Benedict et al. 2012). The market expansion is justified by advanced technical properties, potential cost reduction, and the development of additional disposal options. Furthermore, bioplastics find high consumer acceptance, due to increasing environmental consciousness regarding climate change, the increasing price, and stiff dependence on fossil materials (European Bioplastics 2011a; Shen et al. 2009). In spite of these positive aspects, several researchers (e.g., Harvey and Pilgrim 2011; Shen et al. 2009), international movements, and NGOs for nature conservation and social equity present various concerns about the sustainability of bio-based products, highlighting the risk of land competition. Research is currently ongoing in order to use lignocellulosics as a feedstock, but so far nearly all commercially available bio-based products are made from starch crops or sugar crops as feedstock source (Chen and Patel 2012). Hence, bio-based product sustainability has to be evaluated in an integrated assessment framework: involving food, environment, and energy aspects and

increasing land productivity, rather than expanding existing cultivated areas (Harvey and Pilgrim 2011). It is also argued (Shen et al. 2009) that there is not enough sustainably produced biomass available to cover all the needs of bioresources (such as food, fuels, and materials), and priority has to be given to food production. The scientific debate is open and controversial.

In fact, other studies assert that bioplastics do not damage food availability and prices, and the quantity of food cultivated should be sufficient to the whole global population and huge areas of land are still unused. Land demand would not be a real problem, since agricultural areas are deemed sufficient even considering the growth of land demand expected by 2020 (Carus and Piotrowski 2009). Furthermore, the WWF Denmark published a report in 2009 supported four beneficial points of industrial biotechnology: the substitution of fossil fuels and oil-based materials, improved efficiency, and the potential to create loop systems using wastes (Bang et al. 2009).

However, other key points to be considered in bio-based production diffusion are the necessity to increase the material performance of some products, to reduce the production and processing costs, and the need to minimize agricultural land use and forests, avoiding competition with food production and adverse effects on biodiversity and other environmental impacts (Shen et al. 2009). Finally, even if bio-based products can help to reduce GHG emissions, an uncontrolled and unregulated agricultural production can potentially lead to an increase in other environmental impacts such as eutrophication, land use, and threats to biodiversity (Tillman et al. 2011; Firbank Petit et al. 2008). Nevertheless, it is important to consider that biopolymer production is a relatively new and under development field (Dornburg et al. 2008), and new emerging technologies could avoid these risks. Chen and Patel (2012) deem that energy and carbon profile of biopolymers can be substantially improved by using agricultural waste to provide process energy. According to European Bioplastics (2010a), mechanical recycling of products and packaging made from bioplastics is possible from a technical point of view. For establishing mechanical recycling of bioplastics, two conditions are necessary: (a) the amount in the recycling stream is sufficient to justify additional investments by the recycling industry and (b) the markets for the resulting secondary raw materials are sufficiently large. The feedstock recovery through chemical recycling process allows converting PLA waste into virgin lactic acid, which can afterward be used for all lactic acid productions, including new PLA production (European Bioplastics 2010b). Tecchio et al. (2012) proved the benefits acquired by feedstock recovery comparing the eco-profiles of 1 kg of lactic acid obtained by chemical recycling and virgin source. So far, amounts are still relatively limited; therefore, feedstock or energy recovery and in certain cases composting are recommended now, depending on the product (European Bioplastics 2011b).

A growing application of bio-based production in everyday products is in diaper composition. Indeed, diapers are subject to considerable debate about the relative environmental impacts, related to their manufacturing and end-of-life phase. There is a growing public concern about this point as we look for new ways to ensure the health of children and preserve the environment. In this perspective, the use of bio-based diapers could be seen as one of the solutions.

2 Standard vs. bio-based diaper: state of the art

The conventional disposable baby diaper is a relatively new invention emerging in the 1960s. So far, several studies have been published on LCA and diapers. In 2005, the LCA studies published by the UK Environment agency showed that for both disposable and reusable diapers, raw material production and manufacturing are significant aspects of the life cycle. For disposable diapers, the most significant stage is the end of life (UK Environment Agency 2005). Accordingly to the study results, the largest potential reductions for disposable diapers lie in reducing the impacts before and after use. The environmental hotspots of three different diaper systems in Australia were also assessed (disposable, home-washed re-usable, and commercially washed reusable). At the production stage, the following strategies were identified: (1) reducing diaper mass as it implies almost proportional impact reduction, (2) reducing water and energy consumption during pulping, (3) adopting unbleached or recycled pulp, and (4) using alternative materials, such as hemp and bamboo, in order to improve compostability (O'Brien et al. 2009). Actually, composting all wet diapers would reduce the solid waste associated with disposables, but plastics and non-biodegradable components remain an issue. A cradle-to-gate LCA was performed to evaluate the environmental performance of a wood-based diaper (Clancy et al. 2010). Results show that a reduction in the use of resources or innovation in material is needed during the manufacturing process and that the major contribution to the environmental impacts is embedded in materials, while the diaper packaging, diaper assembly, transport, use, and post-use waste stages have comparatively low impacts. Therefore, for the kind of product material, innovation that results in improved environmental performance in the resource acquisitions is considered a priority. Finally, the environmental improvements which were introduced in Pampers® diapers, from the 2007 version to the new one made in 2010, were compared (Weisbrod and Van Hoof 2011). Sourcing and production of diaper materials contributed most to the environmental indicators and optimization both in the design and materials brought reductions in environmental impacts in the new 2010 version, even if only in low percentages. Non-renewable energy, respiratory

inorganics, and global warming were identified as key impact categories.

Raw material production and end-of-life stage look to be the most critical issues regarding diapers. In order to assess the environmental profile of a bio-based diaper, a life-cycle-based study is strategic. The present study aims to apply life cycle assessment in order to highlight the environmental profile of a bio-based and eco-innovative mass consumption product: a disposable diaper adopting two different kinds of bioplastics (PLA and Mater-bi) that substitute almost completely petrochemical plastics. The aim of the study is to evaluate the environmental performance of the eco-innovative diapers and the related production's stages, focusing on potential areas of further improvement. The study follows ISO 14040 (2006) and ISO 14044 (2006) standards.

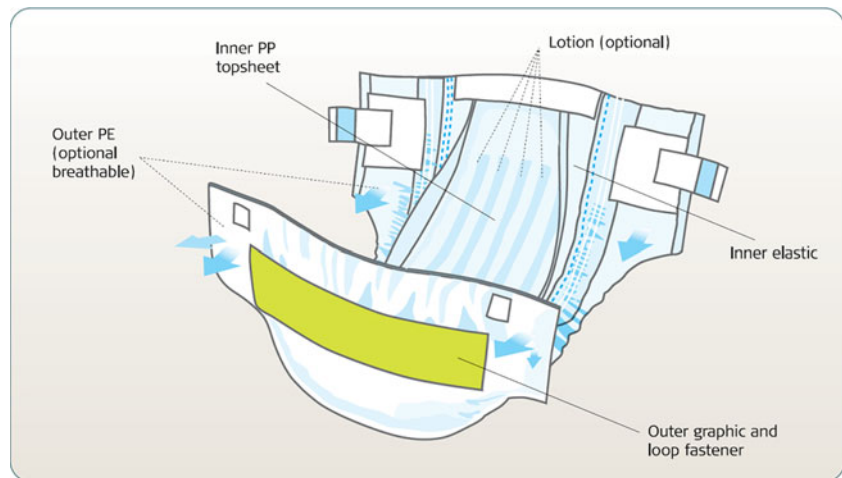
3 Case study: diaper WIP production system

All absorbent hygiene products are designed principally to contain body fluids such as urine and feces; hence, fluids must be readily taken up, distributed, and absorbed by the structure. Various materials and layered constructions are used to engineer these in-use performance requirements precisely.

There are four principal functional layers (EDANA 2007) (Fig. 1): (1) the top-sheet is the layer next to the baby's skin and must be capable of allowing fluid to pass readily through to the next layer; (2) the acquisition and distribution layer (ADL) transfers the liquid to the storage part of the ADL before it is diffused within the absorbent core structure; (3) the absorbent core layer typically relies on an appropriate blend of fiberized fluff pulp and superabsorbent polymer, sodium polyacrylate (SAP), to absorb and retain body fluids; and (4) the backsheet provides a fluid impervious barrier so that moisture is contained within the structure. It is most commonly made of polyethylene film or nonwoven material or both.

WIP S.p.A (Joint Stock Company) is a company situated in the region of Tuscany (Italy), established in 2005. From the beginning, the company chose to design a product that would address and respect sustainability principles, mixing social, economic and environmental aspects and that complied with eco-design requirements. In particular, in its products developed since 2005, the company introduced PLA fibers and used a mixture of biopolymers, such as PLA and Mater-bi, in its composition. They are both used in diaper composition, in order to guarantee the same functional performance of a standard diaper. The quantity of SAP used was drastically reduced from about 32 % in a standard diaper to 15 %, while a major amount of pulp was added (constituting over 55 % of overall diaper weight). Additionally, polypropylene usually used for the top-sheet was substituted by PLA, Mater-bi replaced polyethylene film in the backsheet, and the ADL is composed of a

Fig. 1 Schematic overview of a modern disposable diaper (from EDANA 2007)



mixture of 50 % PLA and 50 % PP. Fluff is made by 100 % organic and certified pulp; it is totally chlorine free (TCF) and produced in accordance with the Program for the Endorsement of Forest Certification (PEFC). As a result, the disposable diaper produced by WIP is made of over 75 % renewable and compostable raw materials. For this reason, in June 2011, the diaper got the compostability certificate by CIC (Italian Composting Association), according to UNI EN 13432:2002. This certificate allows WIP diapers to be considered as organic waste, and this can provide a reduction in the environmental impacts during the end-of-life phase. The machines and air emissions treatment, as well as conditioning, are designed to minimize the energy consumptions and all the electricity used in the plant comes from renewable sources (hydropower, wind power, and photovoltaic). WIP supply chain is limited to countries in European Union, except for PLA that is produced in the USA.

4 Life cycle assessment of the bio-based diaper

4.1 Goal

LCA methodology was used to evaluate the environmental performances of WIP diapers, in order to assess the potential environmental impacts related to its production and to address the manufactures on further environmental improvements. The goals of this study are to assess environmental benefits coming from the use of biopolymers in these kinds of products, to verify that the product conforms to sustainability principles, and to identify possible improvements.

4.2 Function and functional unit

The function of the system is the manufacturing of WIP diaper. The company's aim is providing a healthier and more environmentally friendly product for children not yet toilet

trained. The functional unit chosen is 1 diaper. WIP diaper performances in collecting excreta were tested and equal to standard diaper; hence, the two products have the same functional properties.

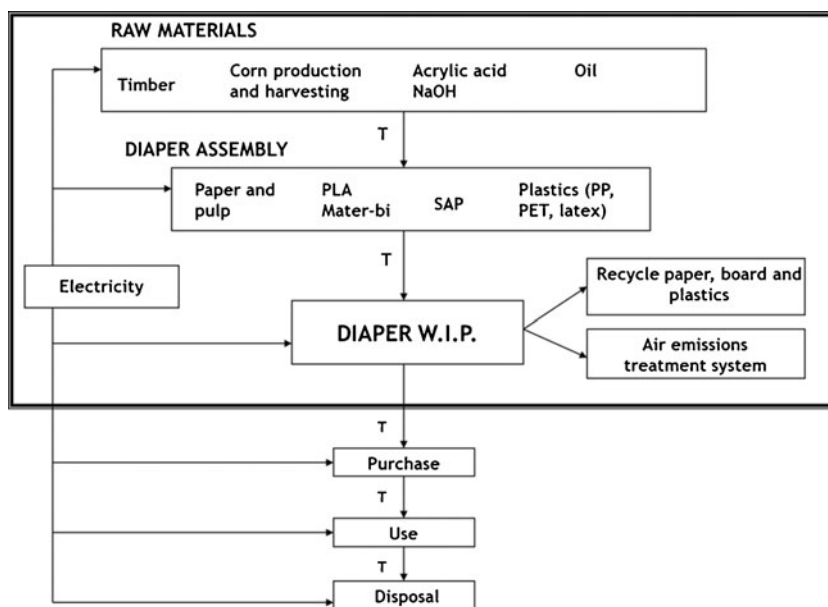
4.3 Product system and system boundaries

The system under study does not include the entire life cycle of the product, but is limited to factory gate (cradle to gate analysis). At this stage, the end life of the diaper is excluded, as end-of-life options are still under evaluation (data about the composting supply chain are still not available). Hence, distribution, use, and disposal phases of the diaper are excluded. The life cycle phases include (Fig. 2) raw materials and their transport, diaper manufacturing (at WIP plant in Tuscany, Italy), and packaging. Regarding raw materials, all items are included, for completeness, in order to evaluate if and how materials can affect the diaper eco-profile, though they give a low contribution to the total material amount. Energy consumptions due to diaper production and air emissions treatment system are included, as well the recycling of paper, board, and plastics wastes. System boundaries are shown in Fig. 2. Infrastructure and machineries used are excluded, due to lack of data and relevance in this case study.

4.4 Assumptions

Performing the study, the following assumptions were adopted to overcome data gaps. First, the functional unit was chosen as 1 diaper. WIP diapers are produced in four different sizes, according to weight and age of children. For each size, the amount of materials used is different; hence, it was decided to use average data of the two most sold sizes (midi and maxi, representing about 80 % of sales). Second, packaging of raw materials was not considered because of the lack of reliable data. A third assumption regards SAP and its component, zinc acetate dihydrate. SAP is one of the

Fig. 2 System boundaries (bold box) of the case study. T “transports”



core components of WIP diapers, and its main function is liquid absorption, while zinc acetate dihydrate is used as cross-linker in SAP polymerization. Both are not included in Ecoinvent database nor in other databases available with commercial software Simapro 7.2; hence, literature data and patent document data were used to model their manufacturing processes (Buchholz 1996; Hughes and Navrotsky 2011; Parks 1981; Sanderson and Sadiku 2003). Sanderson and Sadiku (2003) proposed an efficient technique of SAP production in which the heat of polymerization was used for solvent removal. This showed better energy efficiency than the solution or emulsion polymerization methods for preparing SAP. A sodium hydroxide solution and a mixture of acrylic acid, water, and zinc acetate dihydrate react producing the desired product. Energy and raw materials information were collected from Sanderson and Sadiku (2003), while information about reaction procedures come from Parks (1981).

Fourth, PLA is a thermoplastic aliphatic polyester, derived from renewable resources, such as corn starch. The PLA supplier for WIP is NatureWorks LLC (2011), company located in Nebraska (USA) and the first commercial producer for PLA in the world (Vink et al. 2003). As reference for its production, the Ecoinvent process NatureWorks PLA Ecoprofile 2009 (referred to 2003) was used and completed with update information (i.e., air emissions, water, and energy consumption) from Vink et al. (2010). Finally, for road transports, the use of a lorry 16–32 t Diesel EURO 3 was hypothesized.

4.5 Data sources and inventory

Data used in this case study are a combination of primary and secondary data. Primary data provided by WIP S.p.A are: (1)

amount and kind of raw materials, (2) wastes, (3) transports, and (4) energy consumption of system production. Secondary data are related to the processes used (i.e., energy mix, lorry for transports, process manufacturing of raw materials) and derive from Ecoinvent database (Althaus et al. 2007; Hischier 2007; Spielmann et al. 2007; Dones et al. 2007). As mentioned before, average data from midi and maxi sizes of diapers were used to perform the study. There is no difference in the energy needed to manufacture the different kinds of diapers; hence, the allocation procedures regard the total amount of diapers produced. Proprietary concerns prohibit providing details on all specific inputs, except for general data on components and raw materials used. Table 1 summarizes the main features regarding diaper components and their transports.

Table 1 WIP diaper components, raw materials, and distance covered for transport

Component	Name and description	Amount (%)	Transport (km)
Core	Fluff TCF and PEFC (Pulp)	50–55	2,315
	SAP	10–15	471
	Tissue (Pulp)	2–4	103
Backsheet	Film Mater-bi	5–6	137
ADL	50 % PLA 50 % PP	1–2	9,327
Cover	PLA	4–5	9,327
Barrier side	Spun bond 100 % PLA	4–5	11,052
	Filament yarn (Latex)	<1	1,212
Frontal tape	White paper	<1	389
Outer fasteners	Elastic laminated (PET)	1–3	394
	Closure Tape (Paper)	1–2	923
Adhesive (1)	Hot melt dispomel cool (PET)	2–3	385
Adhesive (2)	Hot melt dispomel (PET)	<1	385

Raw materials are produced far from the WIP site (see Table 1). Indeed, few companies produce the organic raw materials needed by WIP, and the decision to privilege them obliges WIP to choose most of their suppliers far from its production site. All data regarding the supply of raw materials were provided by the company. The distances are always covered by lorries, except for a short trip (59 km) covered by train and the transport by ship of PLA (5,851 km).

4.6 Life cycle impact assessment methodology and sensitivity analysis

Life cycle impact assessment (LCIA) was applied at midpoint level and includes both mandatory and non-mandatory elements according to ISO 14044 (2006): impact categories' selection, classification and characterization, plus normalization phase. The normalization phase was applied in order to identify which categories have greater environmental impacts and which should be the areas of major concern for the manufacturer. The impact assessment method applied is ReCiPe 2008, incorporated into the SimaPro 7.3.2 software developed by PRé Consultants (2008); ReCiPe is a follow-up of Eco-indicator 99 and CML 2002 methods, but all impact categories have been redeveloped and updated (except ionizing radiation). It is one of the most updated methods, combining midpoint and endpoint methodologies in a consistent way and listing a comprehensive number of impact categories (EC-JRC 2011). In order to check the consistency of the results, a sensitivity analysis using IMPACT 2002+ method (Joliet et al. 2003) was performed. Energy-related issues were evaluated through the cumulative energy demand, which calculates the primary energy use through the life cycle of the product). Thus, the CED method is useful to gain a general view of the energy-related environmental impacts in a life cycle and for a first comparison of individual products (Frisknecht et al. 2007).

5 Results

5.1 Characterization phase

The results obtained, and the relative contribution of the considered stages, are presented in Fig. 3 (see Table S1, Electronic Supplementary Material, for absolute values). The contributions of raw materials, transports, and energy consumption are outlined. Pulp TCF shows greater environmental impacts to seven out of 18 categories (terrestrial acidification, marine eutrophication, agricultural land occupation, urban land occupation, natural land transformation, metal depletion, and water depletion), and it is responsible for 24 to 94 % of the total life cycle impact. This may be

justified by the amount of pulp used for diaper manufacturing (more than 50 % of the total weight). This hypothesis is confirmed by the fact that for two categories (terrestrial acidification and metal depletion), the percentage impact of this process is comparable to others, less used in diaper composition, e.g., PLA. In addition, in another four of the seven categories (agricultural land occupation, urban land occupation, natural land transformation, water depletion), the high impact of pulp TCF is also attributable to its organic nature (and hence the agricultural processing needed to produce it), as well as its amount. Processes that contribute most were found to be the use and the extraction of wood to produce pulp (agricultural land occupation, urban land occupation, natural land transformation), the use of iron (metal depletion), the use of sulfur dioxide (terrestrial acidification), and the amount of water necessary (water depletion) in pulp production. SAP appears to be the second most important element for five categories out of 18 (human toxicity, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity), with a contribution from 34 to 51 %. Main contributors, for all the impact categories mentioned, are coal and nuclear energy included in the electricity country mix of Germany, where SAP is produced. Even if its amount in the diaper is negligible, SAP has clear impacts of toxicity for many environmental sectors, and no other materials or processes contribute in such a relevant way. PLA and transports are the main sources of impact for three categories: PLA affect most particulate matter formation, terrestrial ecotoxicity, and fossil depletion, while transports affect ozone depletion, photochemical oxidant formation, and marine eutrophication (as already pointed out in Groot and Borén 2010). For PLA, main contributors are the corn production (terrestrial ecotoxicity), the coal used for energy requirements during the production process of PLA (fossil depletion), and treatment of maize starch production effluent (particulate matter formation). For what concerns transports, processes with the greatest environmental burdens are the operation of lorries (photochemical oxidant formation and marine eutrophication) and the transport of crude oil from refinery. Contribution of energy consumption is negligible.

5.2 Normalization phase

In order to assess the relative importance of each impact category and establish which processes have the greatest environmental burden, normalization phase was performed using ReCiPe 2008 method. One category, water depletion, is excluded from this analysis, since several uncertainties about the impact factors used still exist.

According to Fig. 4 (see Table S2, Electronic Supplementary Material, for absolute values), four categories have a greater contribution compared to the others: (a) human toxicity, (b) freshwater eutrophication, (c) marine ecotoxicity, and (d)

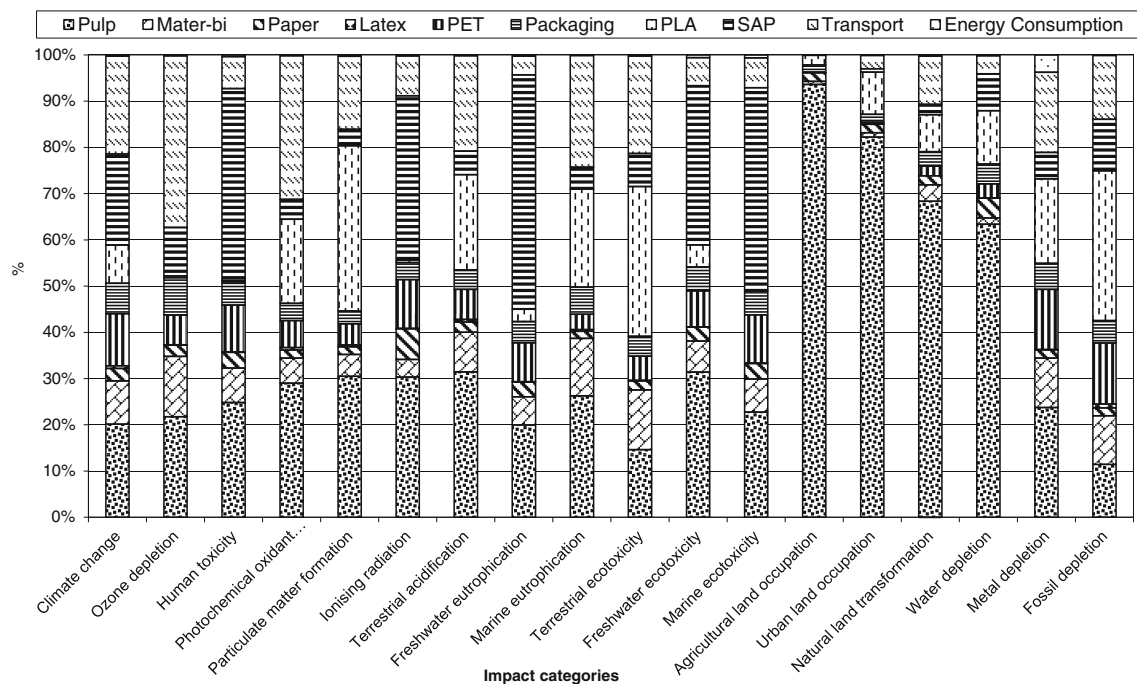


Fig. 3 Results of characterization stage (LCIA method ReCiPe 2008) related to the functional unit of 1 diaper. “Others” represents the raw materials whose overall contribution is less than 4 %

natural land transformation. The first three categories show that the most significant element is SAP, whose contribution ranges from 44 to 51 %, while pulp TCF has the greatest environmental burden only for natural land transformation category, amounting to 68 %. These results change the ranking of most impacting elements with respect to

characterization. Indeed, looking only at the results obtained for the characterization phase, pulp TCF looks like the most significant material for the majority of considered categories. However, the normalization phase highlights that SAP is the major contributor of the environmental burden, in spite of the small amount used in diaper manufacturing.

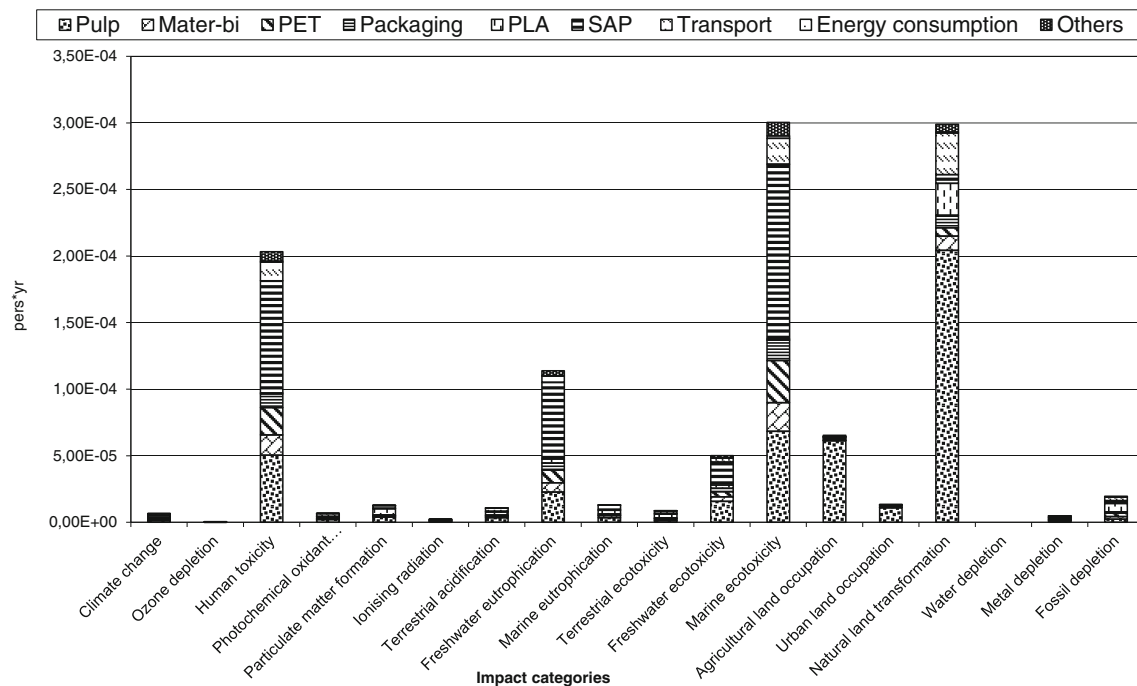


Fig. 4 Normalized results (LCIA method ReCiPe 2008) for WIP system related to the functional unit of 1 diaper

Since developments about land use categories in LCIA methods are still ongoing (EC-JRC 2011; Hauschild et al 2012), the evaluation of natural land transformation impacts requires further investigations. Hence, a sensitivity analysis with IMPACT 2002+ was performed, to assess the robustness of results.

5.3 Sensitivity analysis

Key variables and assumptions were tested to determine their influence on the results of the inventory analysis and impact assessment. Since it is the purpose of this paper to identify possible improvements or to check hotspots of the product, a sensitivity analysis that compares standard diapers and WIP diapers was performed, and results were tested with another LCIA method, IMPACT 2002+. New concepts and methods have been developed for IMPACT 2002+ to ensure they better fit the comparative scope of LCIA, as for human toxicity and ecotoxicity categories and for resources (EC-JRC 2011). ReCiPe and IMPACT 2002+ use both a midpoint/endpoint approach, but the impact models behind are different and may emphasize different aspects related especially to toxicity and energy related impacts. Finally, to highlight energy-related considerations, CED was calculated.

WIP S.p.A. is an Italian firm but its sales products all over Europe. For this reason, the comparison between WIP diaper and a standard one was made with reference to the European situation, which is more representative for the whole market. Reference data for standard diaper used for comparison are those published by UK Environment Agency (2008) (see Table S3, Electronic Supplementary Material). As occurs for other countries, most of the disposable nappies that are sold in the UK are also manufactured in the UK, although several raw materials are obtained from other European countries or from North America. The functional unit is 1 diaper. Both WIP and standard diapers have the same functional performances. Due to lack of data about transports and wastes produced during the life cycle stages of standard diapers, the comparison is restricted to the inclusion of raw materials and energy consumption.

As illustrated in Fig. 5, WIP diaper performance has room for improvements. These improvements are not only in the design and the finished product but also and in great deal in the life cycle stages of the raw materials used. WIP diapers perform worse in the impact categories regarding water consumption, land use, and land occupation, due to the use of bio-based as raw materials. For categories related to fossil and mineral resources, eutrophication, and ecotoxicity, these results look quite odd. It may occur because of the use of fossil fuels for the production of raw materials and the use of pesticides, fertilizers, etc. during farming stages of corn. The results of the normalization (Fig. 6) show that the standard

diaper has the most significant impacts in the categories with a greater relative weight, so it is possible to state that WIP diapers can bring environmental benefits with respect to the most common disposable diapers. WIP diapers show better results for human toxicity, freshwater eutrophication, and marine ecotoxicity, ranging from 21 to 26 %. Higher values are attributed to natural land transformation, with a double contribution compared to standard diapers, due to the greater amount of pulp used in WIP diaper.

Results were checked applying IMPACT 2002+ assessment method (see Figs. S1 and S2, Electronic Supplementary Material). Some differences resulted compared with ReCiPe outcomes: Pulp is confirmed as a major source of impacts, but PLA gains the second position in order of magnitude. The impact categories more affected by PLA are respiratory inorganics and non-renewable energy. This result is consistent with the concerns reported. Indeed in the analysis of ReCiPe, PLA environmental profile showed a strong use of fossil and nuclear fuels during its production life cycle and use of pesticides and fertilizers during farming stage, particularly emphasized by the ReCiPe method. The IMPACT2002+ method shows greater contributions also for transports, compared to results obtained with ReCiPe. Energy consumption within the factory gate confirms its negligible impact. An uncertainty analysis was carried out to assess the variability of input data on the results of comparison between WIP and standard diaper. Monte Carlo simulations were performed in SimaPro 7.3.2. Each simulation consisted of 1,000 iterations, which produces a representative picture of the complete uncertainty distribution of the model outcome. The results allow showing whether the differences provided by the previous comparisons (see Figs. 5 and 6) are significant. In general, it is possible to assume that if 90 to 95 % of runs are favorable for a product, the difference between the products may be considered significant. Therefore, the uncertainty analysis confirms the results reported in Figs. 5 and 6, and the differences could be not significant for the categories natural land transformation and human toxicity (see Figs. S3 and S4, Electronic Supplementary Material).

A further analysis was conducted to highlight the different sources of energy used during the product life cycle; hence, CED was calculated for both diapers. Energy production processes are classified into non-renewable fossil energy (e.g., oil, natural gas, coal); non-renewable nuclear energy flows; renewable biomass energy flows; renewable wind, solar, and geothermal energy flows; and renewable hydro-energy flows (Frischknecht et al. 2007). CED value is higher for WIP diapers than for standard diapers, equal to 3.3 and 2.4 MJ_{eq}, respectively (see Fig. S5, Electronic Supplementary Material). The pulp used and the associated biomass is a great contribution to CED value (especially in WIP diaper), strongly connected to the quantity used.

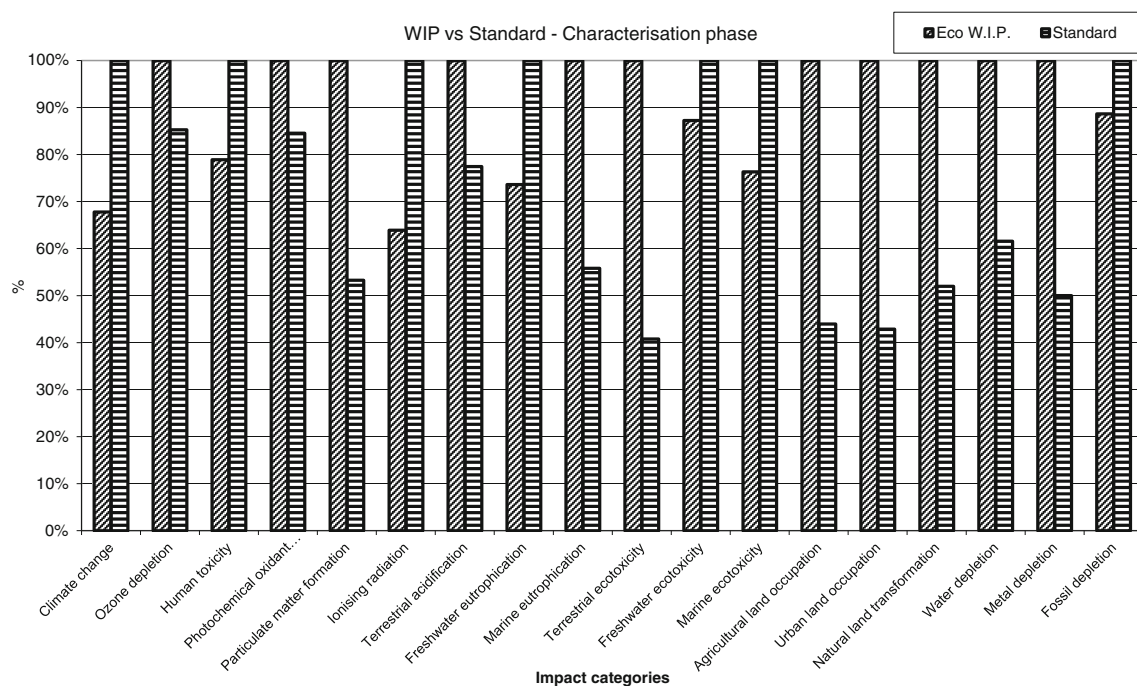


Fig. 5 Results of characterization (LCIA method ReCiPe 2008) stage related to WIP diaper and standard diaper

Excluding the contribution of renewable biomass energy flows, the CED value of WIP diapers results to be comparable to standard ones (1.6 and 1.7 MJ_{eq}, respectively). The amount of renewable energy flows used to manufacture WIP diaper is significant, equal to 54 % of the total CED. These results confirm the choices of the company regarding the optimization of production and minimization of energy

consumptions. Non-renewable energy related to fossil fuels is reduced by 12 % for WIP diaper compared to standard ones, while the use of renewable energy related to water and wind, solar, and geothermal is increased 4.3 and 5.5 times, respectively.

Since the end-of-life stage of diapers could influence the eco-profile of the product, a further sensitivity analysis was

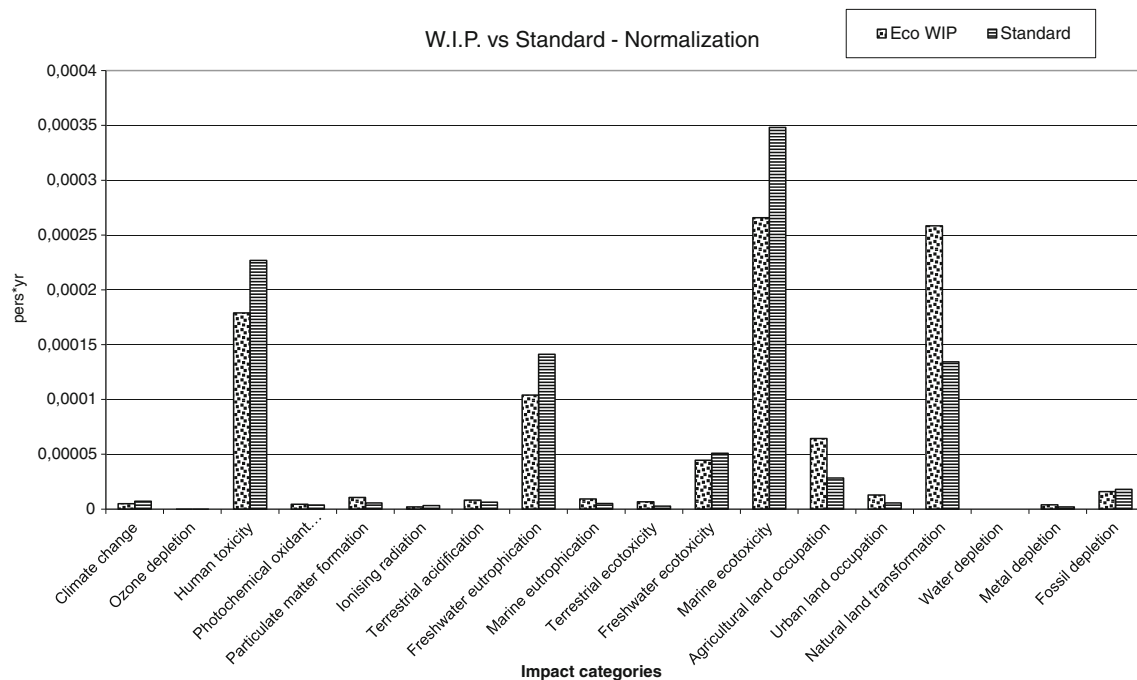


Fig. 6 Normalization stage (LCIA method ReCiPe 2008), comparison of eco-profile for WIP and standard diaper

performed comparing three hypothetical end-of-life scenarios. The three scenarios are: (a) 100 % composting; (b) 37 % landfilling, 43 % composting, and 20 % incineration for WIP diaper; and (c) 65 % landfilling and 35 % incineration for standard diaper. For scenario (a) and (b), primary data from an Italian composting plant were used as reference, while WIP diaper and excreta were considered as biowaste. Italian data were adopted since Italian composting plants have already granted their availability to accept bio-based diaper as a waste (due to the fact that the certification has been awarded by the Italian Association of Composting Plants, according to the European criteria stated by the EU 13432:2002) and primary data were available.

Considering the geographical scope of our study, percentages of waste disposable options for scenario (b) and (c) were considered according to European Statistics (Blumenthal 2011) and are representative of EU-27 situation. Ecoinvent processes were used to model diaper end of life conditions for landfilling and incineration scenarios. For standard diaper, excreta is designed as being biowaste, fluff pulp as paper, and the remainder as plastic waste (UK Environment Agency 2005). The impact assessment method applied is ReCiPe 2008 (Goedkoop et al. 2009).

As shown in Fig. 7, the introduction of 100 and 43 % composting as end-of-life scenarios improved the environmental performance of WIP diaper, compared to standard

one. WIP diaper appears to be more impacting for the categories that are most influenced by the production phase (e.g., agricultural land occupation, urban land occupation, natural land transformation, see Table S4, Electronic Supplementary Material, for details). However, composting improves WIP performance in some impact categories where *cradle-to-gate* results were critical, such as terrestrial acidification, terrestrial ecotoxicity, and marine eutrophication. Further analysis would be necessary to improve the robustness of these results.

6 Discussion and conclusions

The study proves that integrating sustainable principles into the product design has positive feedbacks from the environmental point of view. It is clear that the question is complex and its implications involve all features of sustainable development especially in this historical seeking for green growth and bio-based economy.

Within this context, as being bio-based is not sufficient for being considered environmental friendly, the comprehensive assessment of the environmental benefit of bio-based products is paramount. WIP diapers proved to have several positive elements, but also some room for improvement. SAP reduction in diapers increases criticisms regarding the amount of

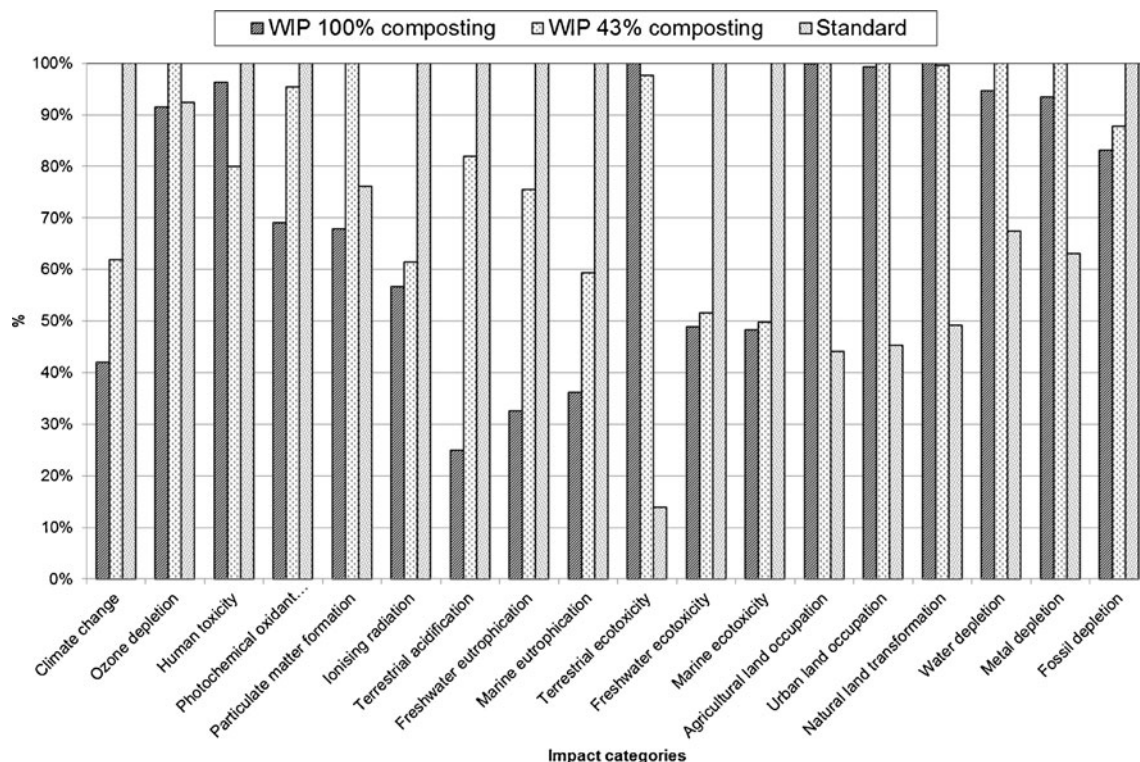


Fig. 7 Results of comparison between WIP and standard diaper, including three end-of-life scenarios (characterization stage, ReCiPe 2008 method): (a) WIP 100 % composting; (b) WIP 37 % landfilling,

43 % composting, 20 % incineration; (c) standard diaper 65 % landfilling, 35 % incineration

pulp used, but at the same time, its negative balance with regards to toxicological issues makes this raw material far less preferable. Use of biopolymers can have strong positive effects on the production life cycle of the diaper, but the study also highlights several concerns about their polluting production phases, i.e., agricultural practices and energy generation. Advantages related to PLA renewability and more favorable end-of-life options (such as composting) are an evidence in WIP diaper eco-profile. Nevertheless, the use of over 60 % of non-renewable energy sources and an intensive agriculture system in the PLA production phase partly worsens the environmental performances of W.I.P. S.p.A compared to those achievable if 100 % renewable energy sources were used for PLA production, as it is for the WIP diaper assembly in the WIP S.p.A. production site. Impacts generated by transport are less significant when compared to others, but sensitivity analysis stressed the importance of reducing distances along the supply chain, as far as possible. The energy policy of WIP S.p.A proved to be effective, since the environmental burdens related to electricity consumption are quite low. In conclusion, the introduction of biopolymers in diaper composition could lead them to be preferable compared to standard diapers, but criticisms arise, which need to be solved, in order to avoid the risk of burdens shifting. Further development and research are necessary, but improvements could result in having bio-based polymers even more competitive and capable to replace fossil-based ones in the future. Finally, the sensitivity analysis conducted about possible end-of-life scenarios highlighted a significant potential improvements of WIP diaper performances in case of partial or total composting of the product. Furthermore, it is remarkable to consider that through the LCA methodology, it is not yet possible to account for the benefits induced using pulp produced according to certification schemes (such as PEFC).

Results obtained applying two different LCIA methods highlighted some discrepancies and the limits existing in current methodologies regarding land use categories. Methods based on different conceptual models emphasize different impact categories in the results; hence, it is important to undertake sensitivity analysis of different methods for exploring the robustness of the results.

Further crucial improvements are related to: (a) geographical differentiation, as many impact categories are already known as being sensitive to relevant variability due to location (see an overview in Sala et al 2011), and (b) biotic resource impact assessment, as many impact assessment methods model only abiotic resources, without comprehensively covering impact related to biotic ones (Klinglmaier et al. 2013).

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